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AN ANALYSIS OF AIR LEAKAGE THROUGH LONGWALL WASTES IN LINGAN COLLIERY

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AN ANALYSIS OF AIR LEAKAGE THROUGH LONGWALL WASTES IN LINGAN COLLIERY

by

D.M. Hamilton* and A.W. Stokes**

ABSTRACT

In the Lingan Colliery ventilation air is lost through the caved wastes behind advancing longwall coalfaces. The airflow in the intake and return airways which service the face can be measured and the leakage determined. This paper presents an analysis of the air leakage in Lingan Colliery's 4W longwall. Reynolds number of the leakage flow was calculated by two independent methods. One utilizes Kozeny's hydraulic model for flow through a porous medium and the other treats the caved gob area as a system of parallel smooth pipes. Both methods provide a better understanding of the flow characteristics of the air leakage.

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ANALYSE DES FUITES D'AIR À TRAVERS LES REMBLAIS D'EXPLOITATION PAR LONGUE TAILLE À LA HOUILLÈRE LINGAN

par

D.M. Hamilton* et A.W. Stokes**

RÉSUMÉ

L'air de ventilation à la mine Lingan s'écoule à travers les remblais derrière les fronts de taille exploités par la méthode de longue taille. Le débit du courant d'air des voies d'aérage d'entrée et de sortie aérant le front de taille, peut être mesuré et la perte d'air déterminée. Ce rapport présente donc une analyse des fuites d'air sur le front de longue taille 4W, à la mine Lingan. Deux méthodes séparées ont servi à calculer le nombre de Reynolds du débit d'air de la fuite. Une de ces méthodes utilise le modèle hydraulique de Kozeny pour calculer le débit d'air passant à travers un milieu poreux et l'autre traite la zone de remblais, comblant les vides d'exploitation, comme un réseau de tuyaux lisses parallèles. Enfin les deux méthodes offrent une meilleur compréhension des caractéristiques du débit des fuites d'air.

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INTRODUCTION

The loss of ventilation air through the caved wastes behind advancing longwall coalfaces is a serious problem in the Sydney Coalfield. The leakage is caused by the porous nature of the caved material (gob) and the high differential pressure between the intake and return airways which service the face. It can be seen from Figure 1 that the maingate roadway forms the intake airway to the face and the tailgate the return. Investigations have been conducted by the Cape Breton Coal Research Laboratory (CBCRL) to determine the nature of the gob leakage for various longwalls in the Lingan Colliery. This paper briefly describes the methods used to gather the gob leakage information and then presents an analysis of the data for Lingan Colliery's 4W longwall. The analysis includes calculations of Reynolds number of the flow through the gob and a simulation of the leakage pathways by a parallel pipe system.

MEASUREMENT OF GOB LEAKAGE

Ventilation and geotechnical surveys were conducted in Lingan's 4W longwall to collect gob leakage data. Measuring stations were marked off at 50 m intervals in the maingate and tailgate roadways, thereby dividing the gob into 50 m wide corridors running parallel to the face (Figure 1). The airflow values measured at these stations were used to determine the air leakage across the gob. A vane anemometer was used to measure the airflow at each station whilst the airflow at the fireseal was recorded at regular time intervals to monitor any fluctuations that might occur during the survey. A gauge and tube (pressure) survey of the district was conducted so that the differential pressure across the gob could be determined.

Tracer gas has also been used to measure airflows in the roadways and through the gob. The tailgate airflows are measured by releasing a steady stream of sulphur hexafluoride (SF_6) from a lecture bottle through a limiting critical orifice. The gas is released into the airstream on the face 20 m from the tailgate. After steady state concentrations are reached, air samples are taken at each station along the tailgate. The tracer gas

concentration in each sample is determined and the roadway airflow is calculated using the following relationship:

$$Q = \frac{\dot{v}}{c} \qquad \text{Eq 1}$$

where, Q = Airflow (m^3/s)

$\dot{v}$ = Release rate of SF_6 (m^3/s)

C = Measured concentration of SF_6

Figure 2 shows an airflow profile measured along the tailgate of Lingan 4W.

Tracer gas has also been used to study the airflow through the gob. A steady flow of SF_6 was released from the maingate into the gob through a 2 m injection lance at a point 458 m inbye from the face startline. Air samples taken at the tailgate fireseal were analyzed for the tracer gas concentrations they contained. Figure 3 shows the build up of SF_6 concentration at the fireseal versus time elapsed since the gas release was begun. This curve can be used to calculate the range of air velocities in the gob. For a continuous injection of tracer gas into a ventilation system, the time it takes to reach half the steady state concentrations (t_{50}) at a point downwind equals the average time taken by air moving along the same route to reach that point (Stokes and Stewart, 1985). The time taken for the first traces of the gas to reach the fireseal (t_0) and the time required to reach steady state concentrations (t_{100}) can be used to calculate the range of air velocities in the gob. In 4W the average air velocity through the gob is given by the equation:

$$V = \frac{L}{T} \qquad \text{Eq 2}$$

where, L = Length of flow path through gob
(assume average length is 500 m)

T = t_{50} - (time for air to travel tailgate to fireseal)

= 108 min - 2 min

= 106 min = 6360 s

$$V = \frac{500\ m}{6360\ s} = 0.079\ m/s$$

The active volume through which air moves in the gob can be found from the gob tracer gas injections. The volume equals the average residence time of the air in the gob multiplied by the air loss through the gob. The air loss through the 50 m gob corridor in which the injection was done is approximately 1 m^3/s. Therefore:

$$\begin{aligned} \text{Average active volume} &= t_{50} \times Q \\ &= 6360\ s \times 1\ m^3/s \\ &= 6360\ m^3 \end{aligned}$$

The preceding discussion serves as a brief introduction to some of the techniques used to gather ventilation data in the Sydney Coalfield. A more thorough account can be found elsewhere (Stokes, 1985).

ANALYSIS OF GOB LEAKAGE

Gob leakage can be measured quantitatively but it is also desirable to have a qualitative description of the flow. Is the flow laminar or turbulent? To answer this question Reynolds number must be calculated and this has been done using two independent methods: Kozeny's hydraulic model and simulation of the leakage paths by a parallel pipe system.

Kozeny's hydraulic model was developed for flow through a porous medium. The flow takes place in the irregularly shaped channels provided by the voids of the bed and the model assumes that the channels are formed by capillary tubes running parallel to the direction of flow. The following equation to calculate Reynolds number has been derived from Kozeny's Model (see Appendix A):

$$Re = \frac{\rho V}{Sp(1 - \varepsilon)\mu} \qquad \text{Eq 3}$$

where, ρ = Density of fluid (kg/m^3)

μ = Dynamic viscosity of fluid ($N \cdot s/m^2$)

V = Average velocity of fluid (m/s)

ε = Voidage fraction = Volume of voids/Volume of bed

Sp = Specific area of particle = Surface area/Volume (m^2/m^3)

All of the required information is available or may be assumed. The volume of the voids is equal to the active volume and the volume of the bed is estimated to be the extracted volume multiplied by a factor of three to account for the separation of the roof above the gob (Figure 4). The specific area of the particles must also be estimated. The particles are assumed to be cubes with sidelength X where:

$$0.01 \text{ m} \leq X \leq 0.1 \text{ m}$$

and,

$$\text{Specific Area} = \frac{6X^2}{X^3} = \frac{6}{X}$$

thus the specific areas lie in the range from 60 m^2/m^3 to 600 m^2/m^3.

The second method treats the leakage through the gob as being analogous with a system of smooth pipes in parallel. The total area of the leakage pathways may be found as follows:

$$A = \frac{Q}{V} \qquad \text{Eq 4}$$

where, Q = Airflow through the gob (m^3/s)
V = Velocity of airflow through gob (m/s)

A pipe diameter is assumed and the friction factor for the pipe is determined by the relationship:

$$f = \frac{2gh_f D}{LV^2} \qquad \text{Eq 5}$$

where, h_f = Head loss across gob = Pressure difference/γ (m)
L = Length of flowpath = 500 (m)
D = Assumed diameter (m)
V = Air velocity through gob (m/s)
g = Acceleration of gravity = 9.81 (m/s^2)

Once the friction factor is determined, the Moody diagram can be used to find the Reynolds number which classifies the flow as either laminar

or turbulent. At this point, equations for fluid flow in smooth pipes may be used to calculate a more precise value for Reynolds number which gives a new velocity from the relationship:

$$V = \frac{Re\mu}{\rho D} \qquad \text{Eq 6}$$

If this velocity equals that of the flow through the gob, then the correct diameter has been assumed. Otherwise a new diameter is selected and the process is repeated until the calculated velocity equals the actual velocity of flow through the gob. Finally, the required number of pipes is found to be the total area of the leakage pathways divided by the cross-sectional area of an individual pipe.

RESULTS

The Reynolds number was calculated by both methods for three different flow velocities as determined by the t_0, t_{50} and t_{100} times from Figure 3. The calculations are presented in Appendix B and the main results are shown in Table 1. The Reynolds numbers for both methods were similar and ranged from 5 at t_{100} to 411 at t_0. This suggests that the flow is laminar. The diameter and number of pipes required by an equivalent parallel pipe system is also listed in Table 1.

Table 1 - Results of calculations for three flow velocities

	V (m/s)	Kozeny's Hydraulic Model	Pipe Method	Diameter (m)	No. of Pipes
t_0 = 1380 s	0.362	$41 \leq Re \leq 411$	405	0.0168	12,450
t_{50} = 6360 s	0.079	$10 \leq Re \leq 98$	41	0.0079	258,279
t_{100} = 12,840 s	0.039	$5 \leq Re \leq 54$	14	0.0055	1,079,202

DISCUSSION AND CONCLUSIONS

There may be some error incurred in using these methods to find Reynolds number due to the uncertainty and the number of assumptions which were made. All assumptions were based on past experience with mining operations in the Sydney Coalfield. In using Kozeny's hydraulic model an exact value of Reynolds number could not be determined since a variety of particle sizes are present in the gob. As a result, ranges of Reynolds numbers are given for each flow velocity. The Reynolds numbers calculated by the pipe method fall within the corresponding ranges for the Kozeny hydraulic model indicating that the results are valid.

In the past, airflow through the gob has been treated as laminar. In some instances the flow may be turbulent, but based on the analysis of the leakage in the 4W longwall it seems to be predominantly laminar. Further research would be helpful in acquiring a more complete understanding of gob leakage flow characteristics.

ACKNOWLEDGEMENT

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REFERENCES

1. Michell, S.J. "Fluid and particle mechanics"; First edition; Pergamon Press Ltd.; Oxford; 1970.
2. Stokes, A.W. and Stewart, D.B. "Cutting head ventilation of a full face tunnel boring machine"; For presentation at and publication in the proceedings of the 21st International Conference of Safety in Mines Research Institutes; Sydney, Australia; October 1985.
3. Stokes, A.W. "Air leakage through longwall wastes in the Sydney Coalfield"; To be published in the proceedings of the 2nd U.S. Mine Ventilation Symposium; September 23-25, 1985.

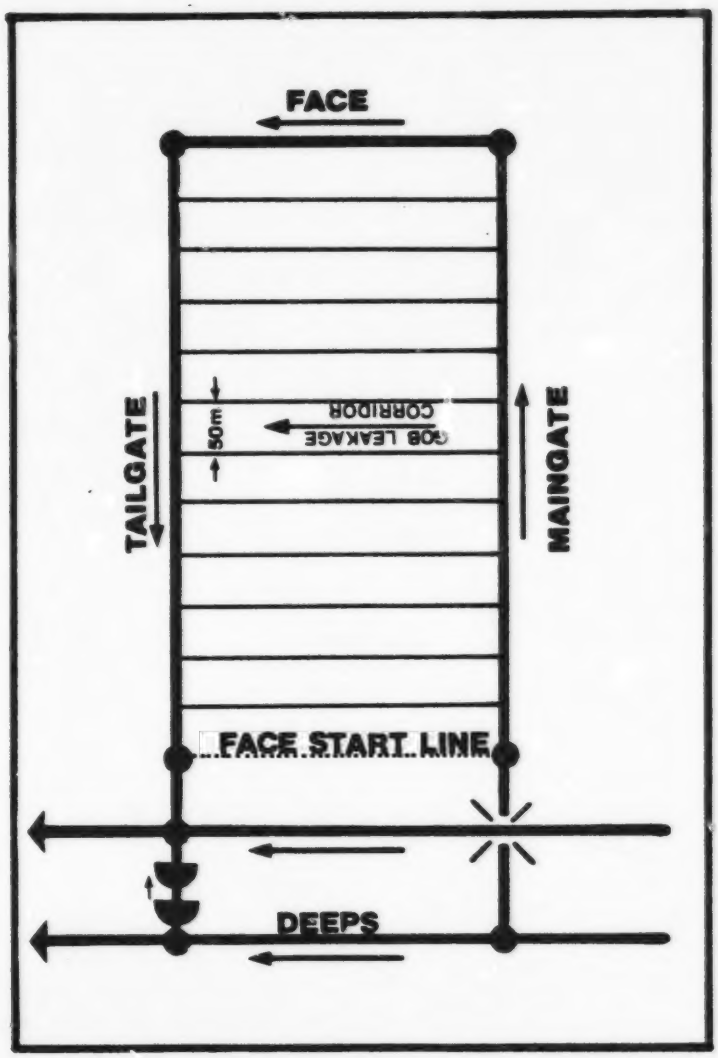

Figure 1 - The gob leakage corridors

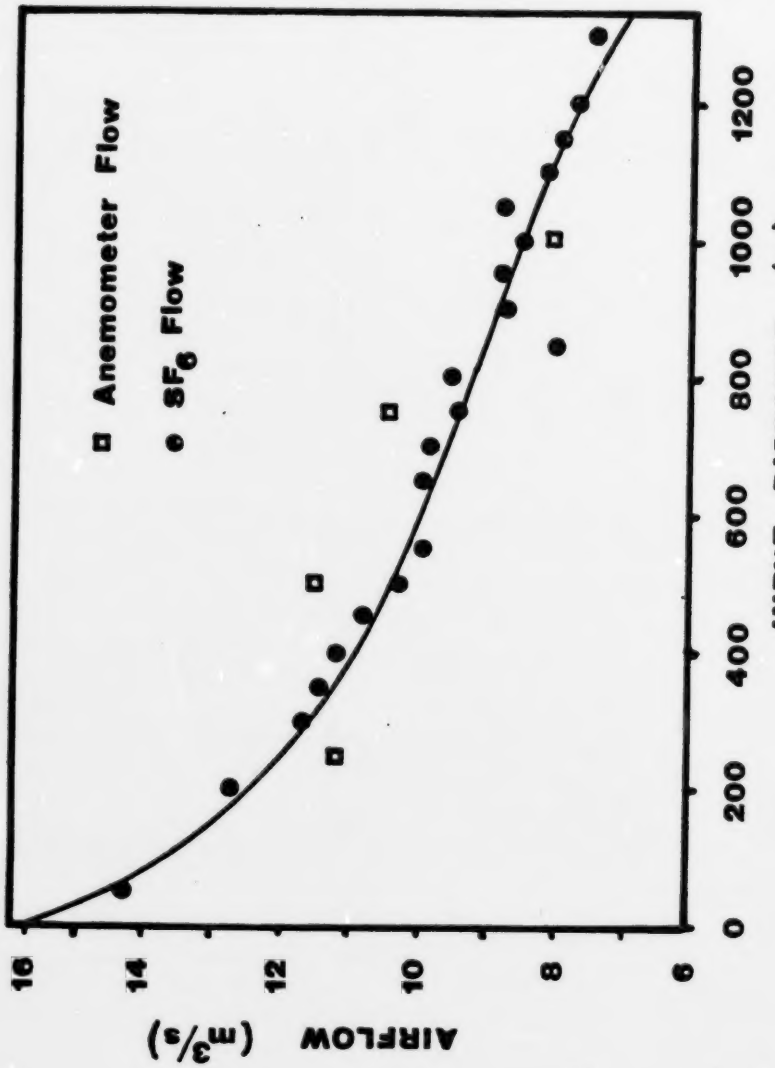

Figure 2 - Four W tailgate airflow profile

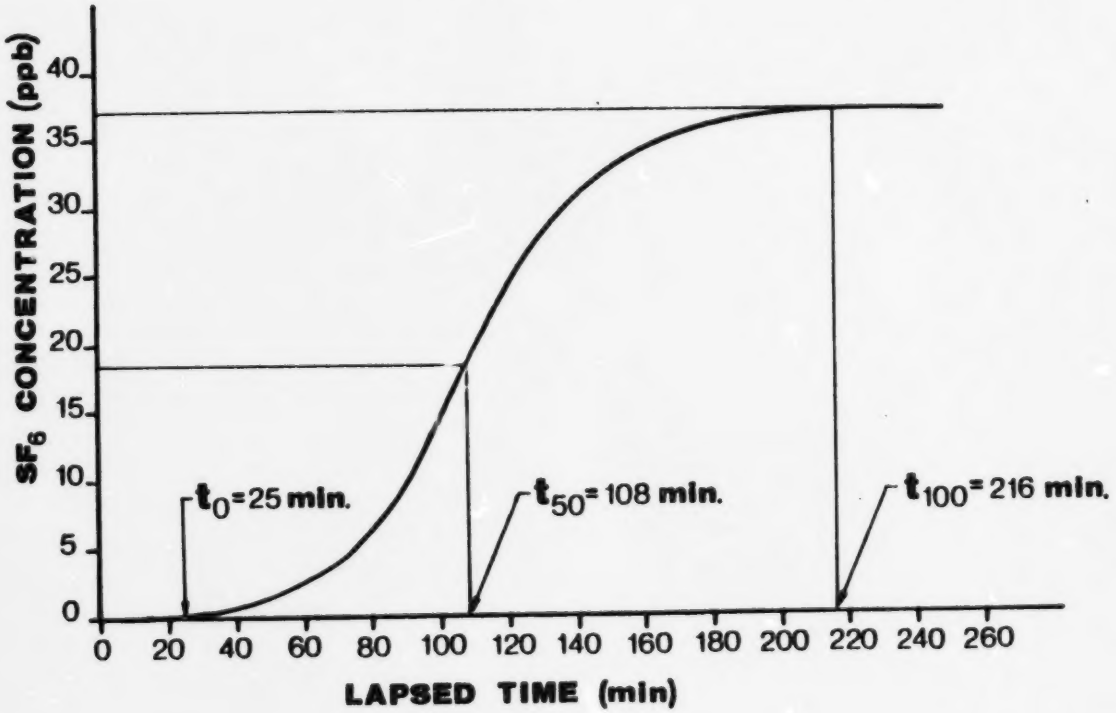

Figure 3 - SF_6 build up at 4W return fireseal

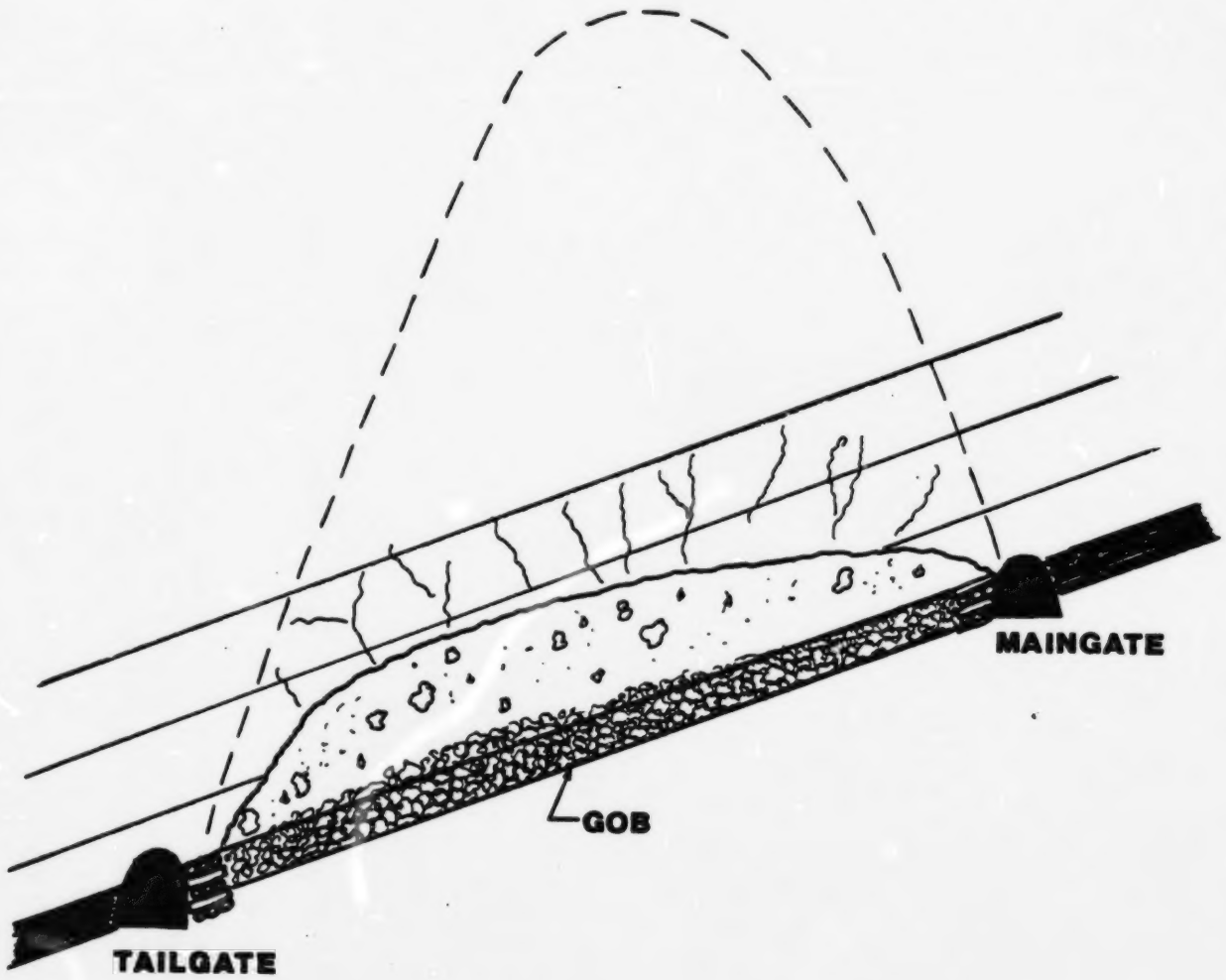

Figure 4 - Roof separation above gob

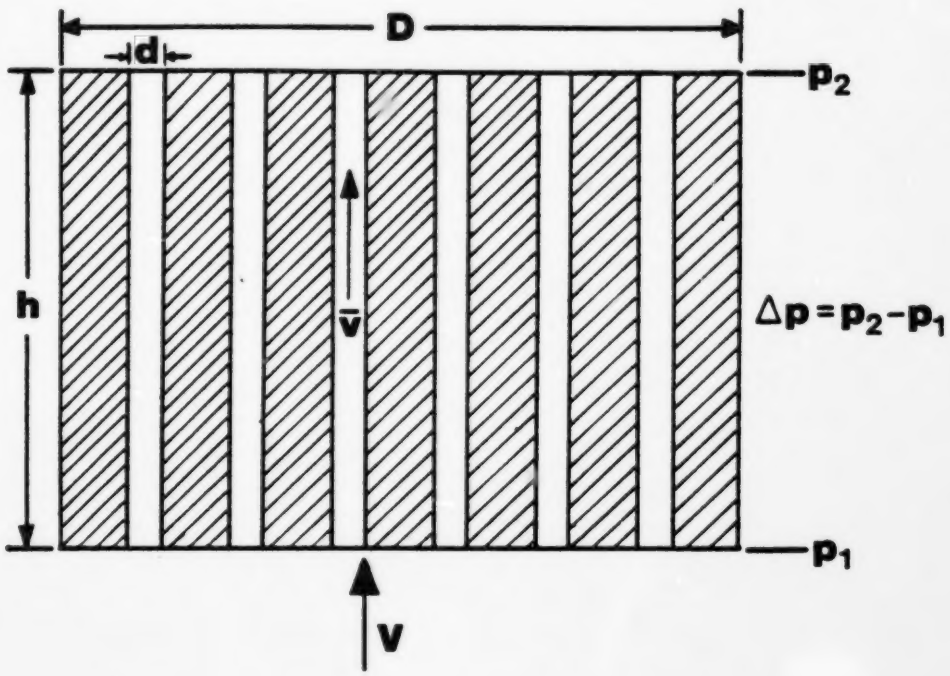

Figure 5 - Kozeny's hydraulic model

APPENDIX A

DERIVATION OF REYNOLDS NUMBER EQUATION USING KOZENY'S HYDRAULIC MODEL

The Kozeny's hydraulic model assumes that the flow channels in a bed of solid particles are formed by capillary tubes running parallel to the direction of flow. Consider in Figure 5 the flow of a fluid through a bed of solid particles contained in a cylindrical vessel of diameter D. Assume that the flow takes place through cylindrical channels of diameter d and length h. Let n be the total number of these channels, then the voidage fraction is:

$$\varepsilon = \frac{\text{volume of voids}}{\text{volume of bed}} = \frac{nd^2(\frac{\pi}{4})(h)}{D^2(\frac{\pi}{4})(h)}$$

$$\varepsilon = n\left(\frac{d}{D}\right)^2 \qquad \text{Eq A-1}$$

Now, let $\bar{v}$ be the average velocity through the parallel channels, then by the law of continuity:

$$VD^2\,\frac{\pi}{4} = n\bar{v}d^2\,\frac{\pi}{4}$$

Substituting for n from this equation in equation A-1 and simplifying:

$$\bar{v} = \frac{v}{\varepsilon} \qquad \text{Eq A-2}$$

Similarly, the hydraulic mean radius may be expressed in terms of the voidage fraction as follows:

Let V_p be the volume of a single particle and A_p be its surface area, then in a uniformly sized bed of N particles,

NV_p = total volume of particles,

NA_p = total surface area of particles,

and

$NV_p\left(\frac{\varepsilon}{1-\varepsilon}\right)$ = total volume of voids.

The hydraulic mean radius is generally defined as the ratio of the cross-sectional area and the wetted perimeter. For a bed of solid particles, this parameter is defined as:

$$R_H = \frac{\text{total volume of voids}}{\text{total surface area of particles}}$$

It follows that:

$$R_H = \frac{NV_p\left(\frac{\varepsilon}{1-\varepsilon}\right)}{NA_p} = \frac{V_p\varepsilon}{A_p(1-\varepsilon)}$$

Let S_p be the specific area of a single particle, then:

$$S_p = \frac{A_p}{V_p} \qquad \text{Eq A-3}$$

and

$$R_H = \frac{\varepsilon}{S_p(1-\varepsilon)} \qquad \text{Eq A-4}$$

The Reynolds number may be defined in terms of R_H, as the characteristic linear dimension by:

$$R_e = \frac{R_H\bar{v}\rho}{\mu} \qquad \text{Eq A-5}$$

Substituting in this equation for $\bar{v}$ and R_H from the respective equations (A-2) and (A-4):

$$R_e = \frac{\left(\frac{\varepsilon}{S_p(1-\varepsilon)}\right)\left(\frac{V}{\varepsilon}\right)(\rho)}{\mu}$$

Simplifying:

$$R_e = \frac{V_\rho}{S_p(1-\varepsilon)\mu} \qquad \text{Eq A-6}$$

APPENDIX B

CALCULATIONS

The leakage has been analyzed for three flow velocities. These were determined using t_0, t_{50} and t_{100} from Figure 3.

t_0 = 25 min - time for gas to travel tailgate to fireseal
t_0 = 25 min - 2 min
t_0 = 23 min = 1380 s

t_{50} = 108 min - 2 min
t_{50} = 106 min = 6360 s

t_{100} = 216 min - 2 min
t_{100} = 214 min = 12,840 s

Length of flow path: 200 m $\leq$ L $\leq$ 1000 m (Use L = 500 m)
Airflow through one 50 m corridor = 1 m^3/s

$$\text{Velocity} = \frac{\text{Distance}}{\text{Time}}$$

$$V_0 = \frac{500\ m}{1380\ s} = 0.362\ m/s$$

$$V_{50} = \frac{500\ m}{6360\ s} = 0.079\ m/s$$

$$V_{100} = \frac{500\ m}{12,840\ s} = 0.039\ m/s$$

REYNOLDS NUMBER CALCULATION USING KOZENY'S HYDRAULIC MODEL

$$R_e = \frac{V\rho}{S_p(1-\varepsilon)\mu}$$

Air at 20°C:

$\rho = 1.20\ kg/m^3$

$\mu = 1.80 \times 10^{-5} N \cdot s/m^2$

Voidage Fraction:

$$\varepsilon = \frac{\text{volume of voids}}{\text{volume of bed}}$$

Volume of voids = air loss x residence time

Volume of bed = extracted volume x 3

$= (2 \times 50 \times 210)\ m^3 \times 3$

$= 63{,}000\ m^3$

Specific Area of Particle:

$$S_p = \frac{\text{area of particle}}{\text{volume of particle}}$$

Assume that the particles are cubes with side length X, where:

$$0.01\ m \leq X \leq 0.1\ m$$

$$S_p = \frac{6X^2}{X^3} = \frac{6}{X}$$

Therefore,

$$60 \leq S_p \leq 600\ (m^2/m^3)$$

Reynolds Number at t_0:

$$R_e = \frac{V_0 \rho}{S_p(1 - \varepsilon)\mu} \qquad \varepsilon = \frac{1\ m^3/s \times 1380\ s}{(2 \times 50 \times 210)m^3 \times 3} = 0.0219$$

$$\frac{(0.362)(1.20)}{(600)(1 - 0.0219)(1.80 \times 10^{-5})} \leq R_e \leq \frac{(0.362)(1.20)}{(60)(1 - 0.0219)(1.80 \times 10^{-5})}$$

$$41 \leq R_e \leq 411$$

Reynolds Number at t_{50}:

$$R_e = \frac{V_{50} \rho}{S_p(1 - \varepsilon)\mu} \qquad \varepsilon = \frac{1\ m^3/s \times 6360\ s}{63{,}000\ m^3} = 0.1010$$

$$\frac{(0.079)(1.20)}{(600)(1 - 0.1010)(1.80 \times 10^{-5})} \leq R_e \leq \frac{(0.079)(1.20)}{(60)(1 - 0.1010)(1.80 \times 10^{-5})}$$

$$10 \leq R_e \leq 98$$

Reynolds Number at t_{100}:

$$R_e = \frac{V_{100}\rho}{S_p(1 - \varepsilon)\mu} \qquad \varepsilon = \frac{1\ m^3/s \times 12{,}840\ s}{63{,}000\ m^3} = 0.2038$$

$$\frac{(0.039)(1.20)}{(600)(1 - 0.2038)(1.80 \times 10^{-5})} \leq R_e \leq \frac{(0.039)(1.20)}{(60)(1 - 0.2038)(1.80 \times 10^{-5})}$$

$$5 \leq R_e \leq 54$$

REYNOLDS NUMBER CALCULATION USING PIPE METHOD

Reynolds Number at t_0:

Total area of leakage pathways = $A_T = \frac{Q}{V_0} = \frac{1\ m^3/s}{0.362\ m/s} = 2.76\ m^2$

$$f = \left(\frac{2gh_f}{LV_0^2}\right)D$$

where,

$g = 9.81\ m/s^2$

$h_f = \frac{\Delta P}{\gamma} = \frac{370\ Pa}{11.8\ N/m^3} = 31.36\ m$

$L = 500\ m$

$V_0 = 0.362\ m/s$

using,

$D = 0.0168\ m$

$$f = \frac{(2)(9.81)(31.36)(0.0168)}{(500)(0.362)^2} = 0.158$$

$$R_e = \frac{64}{f} = \frac{64}{0.158} = 405$$

$$V = \frac{R_e \mu}{\rho D} = \frac{(405)(1.80 \times 10^{-5})}{(1.2)(0.0168)} = 0.362 \text{ m/s}$$

$$\text{Number of pipes} = \frac{A_T}{A_{pipe}} = \frac{2.76}{2.22 \times 10^{-4}} = 12{,}450$$

Reynolds Number at t_{50}:

$$\text{Total area of leakage pathways} = A_T = \frac{Q}{V_{50}} = \frac{1 \text{ m}^3/\text{s}}{0.079 \text{ m/s}} = 12.66 \text{ m}^2$$

$$f = \left(\frac{2gh_f}{LV_{50}^2}\right)D$$

using, $D = 0.0079$ m

$$f = \frac{(2)(9.81)(31.36)(0.0079)}{(500)(0.079)^2} = 1.558$$

$$R_e = \frac{64}{f} = \frac{64}{1.558} = 41$$

$$V = \frac{R_e \mu}{\rho D} = \frac{(41)(1.8 \times 10^{-5})}{(1.2)(0.0079)} = 0.078 \text{ m/s} \approx 0.079 \text{ m/s}$$

$$\text{Number of pipes} = \frac{A_T}{A_{pipe}} = \frac{12.66}{4.90 \times 10^{-5}} = 258{,}279$$

Reynolds Number at t_{100}:

$$\text{Total area of leakage pathways} = A_T = \frac{Q}{V_{100}} = \frac{1 \text{ m}^3/\text{s}}{0.039 \text{ m/s}} = 25.64 \text{ m}^2$$

$$f = \left(\frac{2gh_f}{LV_{100}^2}\right)D$$

using, $D = 0.0055$ m

$$f = \frac{(2)(9.81)(31.36)(0.0055)}{(500)(0.039)^2} = 4.450$$

$$R_e = \frac{64}{f} = \frac{64}{4.450} = 14$$

$$V = \frac{R_e \mu}{\rho D} = \frac{(14)(1.80 \times 10^{-5})}{(1.20)(0.0055)} = 0.039 \text{ m/s}$$

$$\text{Number of pipes} = \frac{A_T}{A_{pipe}} = \frac{25.64}{2.38 \times 10^{-5}} = 1{,}079{,}202$$